Determination of the position of Jupiter from radio metric tracking of Voyager 1

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The Voyager 1 spacecraft flew by Jupiter cm March 5, 1979. Spacecraft navigation was performed with radio tracking data from NASA's Deep Space Network. In the years since then, there has been a great deal of progress in the definition of celestial reference frames and in determining the orbit and orientation of the Earth. Using these improvements, the radio metric range and 1)oppler data acquired from the Voyager 1 spacecraft near its encounter with Jupiter have been re-analyzed to determine the plane-of-sky position of Jupiter with much greater accuracy than was possible at the time of the encounter, The. position of Jupiter at the time of encounter has been determined with an accuracy of 40 nrad in right ascension and 140 nrad in declination. This position estimate has been done to improve the ephemeris of J upiter priori to the upcoming encounter of the Gal i leo spacecraft with Jupiter.

INTRODUCTION

Radio metric tracking data has been used since the inception of interplanetary space exploration to determine the trajectory of the robotic probes. Several analyses have been written that describe t he abi 1 it y of radio metric dat a to determine the position of i nterplanetary spacecraft. [1-3] The ability to determine the plane-of-sky position of spacecraft comes from the signature imposed on the spacecraft radio signal by the rotation and orbital motion of the Earth. This signature can be analyzed to determine the right ascension and declination of the spacecraft. There is also a signature in the spacecraft radio signal, due to the acceleration causeded by a nearby planetary body, which can be used to determine the position of the spacecraft with respect to the planetary body. The combined signatures can be used to determine the position of the planet at the time of the spacecraft encounter.

The diurnal signature in the radio metric data give information about the spacecraft right ascension and declination with respect to the direction of the Earth's spin axis at the time of the measurement. The direction of the Earth's spin axis, and the orbit of the 1 :arth, with respect to a desired inertial celestial coordinate system must be known in order to use the radio metric data to deduce the inertial coordinates of the spacecraft.

The determination of the orbit and orientation of the 1 :arth has been a field of intensive study. The introduction of routine Very Long Baseline Interferometry (V1 .BI) observations in the early 1980's has enabled the definition of a celestial reference fi amc, defined by the positions of extra-galactic radio sources, with internal consistency of about 5 nrad (see e.g. Ref. 4). This is about a factor of 1()() better than optical star catalogs previously used to define the celestial reference frame (See e.g. Ref. 5). The orientation of the Earth is measured by V] .BI with an accuracy of about 5 nrad with respect to the extra-galactic radio sources. Beginning in 1988 the International Earth Rotation Service (11;1-?S) was formed to facilitate reporting Earth orientation in a standard way. The IERS adopted a conventional celestial reference frame defined by the positions of extra-galactic radio sources. Earth orientation measurements with respect to the IERS celestial reference frame are regularly distributed.[6] The orbit of the Earth about the sun is known with an internal accuracy of about 5 nrad from the anal ysis of ranging data to the Viking landers and Lunar Laser Ranging (1 .LR).[7] The same 1.1 .R data can be used to determine the orientation of the Earth with respect to

the Earth's orbit. Comparison of LLR and VLB1 Earth orientation has been used to determine the orientation of the 1 Earth's orbit with respect to the 1 ERS celestial reference frame with an accuracy of about 15 nrad.[8]

The ephemerides of the outer planets has been heavily dependent on optical measurements due to a scarcity of more accurate measurements. The relatively poor accuracy of the optical da(a, and zone errors in the optical reference catalogs, contributed to an apparent discrepancy in the position of Jupiter of 400 km during the Ulysses spacecraft Jupiter encounter in February 1992.[9] This discrepancy and the upcoming encounter of the Galileo spacecraft with Jupiter in December, 1995 prompted a re-analysis of radio tracking data from the Voyager 1 encounter with Jupiter to provide a radio met ric position of J upiter referred to the 1 ERS celestial reference frame.

The closest approach of the Voyager 1 spacecraft to Jupiter occurred on March 5, 1979. Shortly after closest approach to Jupiter, the spacecraft flew within 21,000 km of Io and then within 150,000 km of Ganymede and Callisto. Navigation of Voyager 1 was performed using radio range anti Doppler measurements by the Deep Space Network and by using images of the satellites of Jupiter against background stars taken by the on-board camera.[1 0, 11] The Voyager 1 navigation provided a determination of the 1+alh-Jupiter range at the time of encounter[a] and data for the improvement of the ephemerides of the sate]] itcs of Jupiter.][2] However the large uncertainty of the orbit and orientation of the Earth at that time prevented a useful improvement in the plane-of-sky position of Jupiter. A re-analysis of the Voyager 1 radio tracking data, based on the previous work of the Voyager 1 navigation team and with updated models for the orbit and orientation of the Earth, has been performed to determine the right ascension and declination of Jupiter at the time of the Voyager 1 encounter.

METHOD

Two-way Voyager 1 tracking data was acquired by an antenna from the Deep Space Network transmitting a signal to the spacecraft at a frequency near 2.1 GHz (S-band) with the spacecraft receiving and coherently re-transmitting the signal to Earth at 2.3 GHz or 8.4 G] 1z (X-band). The data employed for the re-analysis spanned 32 days ending a few hours after the closest approach to Jupiter and before the encounter with 10. Doppler measurements were made by comparing the frequency of the received carrier with the transmitted carrier at the DSN antenna. Range measurements were made by determining the delay between the time of transmission of a range code (a set of coherent tones about the carrier) and the time of reception of the re-transmitted range code. The dominant noise on the measurements was due to variations in the charged particle [distribution between Earth and the spacecraft, mostly due to solar plasma. For much of the time, Voyager 1 transmitted coherent signals at both 2.3 GHz and 8.4 GHz. For the re-analysis, only dual-band downlink data was used. Because the charged particle effects are proportional to the inverse of the square of the carrier frequency, the dual-band downlink provides a measure of the charged particle effects on the downlink signal. By interpolating the charged particle effects to the time of the uplink, it was possible to remove most of the el feet on the tracking data.

The spacecraft trajectory was integrated from initial position and velocity conditions using models for the dynamic forces on the spacecraft. The modeled gravitational forces on the spacecraft were due to the masses of the sun and planets, the Galilean satellites, and the oblateness of Jupiter. The relat ive locations of the Sun and planets were based on the JP1. ephemeris labeled DE200[13] but with the orbit of the Earth adjusted to have the correct orientation with respect to the IERS celestial reference frame at the time of encounter.[8] The position of the Galilean satellites were given by 1.icskc.'2 The masses of the Jovian system and the oblateness of Jupiter arc given

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[a] J. K, Campbell, I 982, "Earth-Jupiter Range Fixes from Voyager" , JPL IOM 314.8-35 1(internal document)

by Campbell and Synnott.[11] Other forces modeled were solar radiation pressure and thruster firings.

The Voyager] spacecraft is three-axis stabilized using unbalanced thrusters. Because of torques acting on the spacecraft (mainly clue to solar pressure) the thrusters repeatedly fire to maintain a specified orientation. These thruster firings produce small velocity changes to the spacecraft trajectory. Changes in the orientation of the spacecraft caused a change in the torque on the spacecraft and a change in the pattern of the thruster firings. information about the thruster firings was encoded in the spacecraft telemetry stream but this information was imperfect. Instead of relying on the incomplete telemetry information, the magnitudes of the thruster firings were estimated in two ways: as constant accelerations, while the spacecraft was in a fixed attitude, to approximate the nearly constant thruster firings needed to maintain the attitude, and by impulsive maneuvers which were larger events associated with changes in the spacecraft orientation. In addition, there was cJnC larger impulsive maneuver 12.5 days before Jupiter encounter to correct the spacecraft trajectory. Table 1 gives the acceleration and maneuver times included in the re-analysis. Some information about the history of the spacecraft orientation is no longer available so some of the events in Table 1 were inferred from an examination of tbc tracking data. 1 n principle, the only consequence of estimating too many maneuvers and accelerations is to weaken the solution.

'1'able 1. Modeled thruster firing times

Maneuver time	Acceleration start time
4-FEB-1 979 00:00	01 -FEB-1979 00:00
5-FEB-1 979 12:00	04-FEB-1 979 08:30
9-FEB-1979 04:02	05-1 FEB-1979 12:00
17-] 'FiB-1 979 00:00	09-1 FEB-1979 04:00
18-17EB-1979 18:00	11-FEB-1979 02:00
] 9-FEB-1979 00:00	15-FEB-1979 00:00
21-FEB-1979 03:58	17-FEB-1979 15:00
1-MAR-1 979 23:00	19-FEB- 1979 05:00
3-MAR- 1979 20:00	21-FEB-1979 18:00
	04-MAR- 1979 00:00

Computed values for the tracking measurements were derived from nominal values for the spacecraft epoch state, force models, inertial Deep Space Station locations, and calibration for propagation delays due to Earth troposphere.[14] A least-squares fit to the observed minus computed measurement values was made to estimate model parameters. The estimated parameters included the spacecraft initial state, corrections of the orbital elements of Jupiter, the direction of Jupiter's spin axis, a range bias for each DSN antenna, and parameters to describe the thruster firings. Locations for the stations of the DSN were consistent with the IERS terrestrial reference frame.[6] The station locations were mapped from Earth-fixed locations to inertial space using models for precession, nutation, solid Earth tides, and calibrations for polar motion and length of day variations and corrections to the standard nutation model in the manner defined by the IERS.

The estimated uncertainty for the spacecraft trajectory depended on assumed a priori uncertainties for the estimated parameters, the data arc and data weights assumed, and on a priori uncertainties for model parameters that arc not estimated. The effect of uncertainties of non-estimated model parameters is included through the use of consider analysis.[5] The assumed a priori information for estimated and consider parameters is summarized in Table 2. The a priori uncertainties for spacecraft initial state were large enough to leave it essentially unconstrained. The thruster firing uncertainty levels were based on the level of variation as recorded by the telemetry information[1] and by checking that the estimated corrections to the acceleration were significantly

smaller than the a priori uncertainty. The uncertainty in the position of Jupiter ant] in the Jupiter spin axis direction were set large enough so as to not influence the solution. Because range calibrations were not recovered for the re-analysis, the DSN range biases were set to a value corresponding to the total delay through the ground station. DSN station locations arc currently known to 3 cm but because of uncertainty in the rate of change of station locations due to plate tectonics this was increased to 10 cm uncertainty for the 1979 encounter data (and was large enough to include uncertainties in Earth orientation). The uncertainty in the orientation of the Earth's orbit comes from the comparison of VLBI and M JR Earth orient ation.[8] The uncertaint y in the t roposphere calibrat ion is t aken from Robi nson.[@] The uncertainty in the oblateness of Jupiter's gravity field is from Campbell and Synnott.[12]

Table 2. Estimated and considered parameters and their uncertainties

Estimated Parameters	Uncertainty
Spacecraft initial position	10^5 km
Spacecraft initial velocity	1 00 km/sec
Impulsive maneuvers (each component)	1 cm/sec
Thruster accelerations (each component)	10^{11} km/s^2
Jupiter right ascension	500 nrad
Jupiter declination	500" nrad
1 Earth-Jupiter range	1 00 km
Jupiter spin axis, right ascension	0.1°
Jupiter spin axis, declination	0.1°
DSN range biases	3 km
Consider Parameters	
DSN station locations	10 cm
Earth orbit orientation w.r.t. IERS frame	15 nrad
Troposphere zenith delay	4 cm
Jupiter oblateness (J2)	0.01%

1<11s111,'1's

Figures 1 and **2 show the** post-fit data residuals. The Doppler data residuals have a root-mean-square (r"111s) of 0.1 111111/s. Most of the data points have averaging times much longer than the standard 60 s.]f the data noise is assumed to be white-frequency noise, then the Doppler data residuals correspond to an r.m. s. of 0.3 mm/s for 60 s averaging t ime. The solar plasma is known to impose more noise on the Doppler data at low frequencies[16] so for the final estimate the Doppler data were conservatively weighted at 1 mm/s uncertainty for 60 s count time, even though the solar plasma was partially calibrated. This loose weighting prevents small signatures in the Doppler data from excessively influencing the solution estimates and increases the formal uncertainty. The range data have an r.m.s. of 3.2 m and were weighted *at 4* m in the solution.

[@] S. E. Robinson, 1986, "Errors in Su rface Model Estimates of Zenith Wet Path Delays Near DSN Stations", JPL IOM 335.4-594 (internal document)
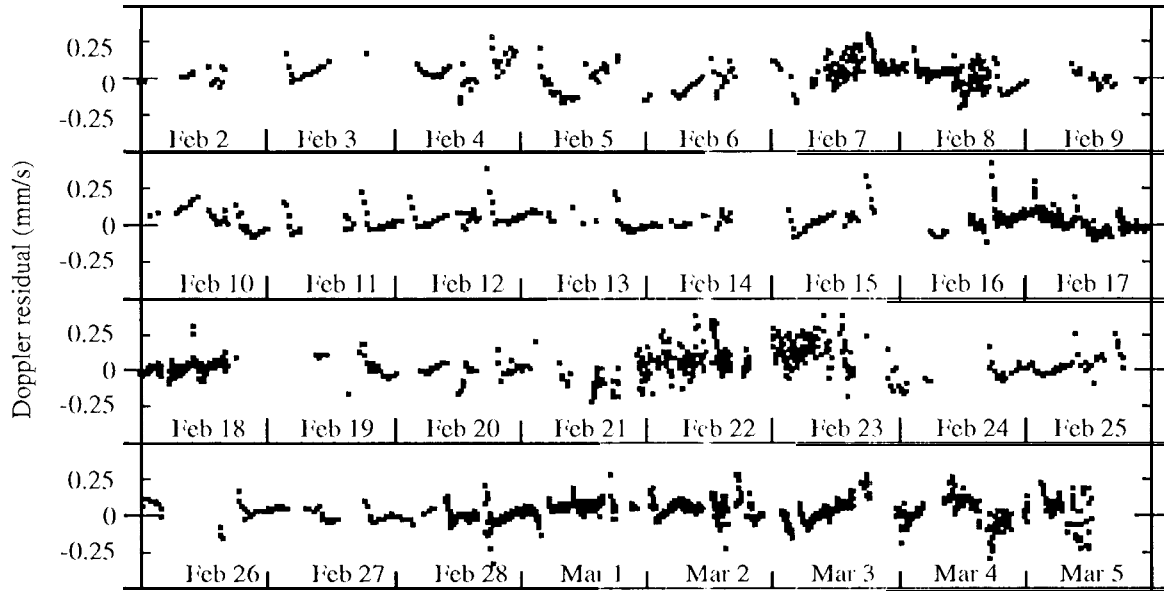
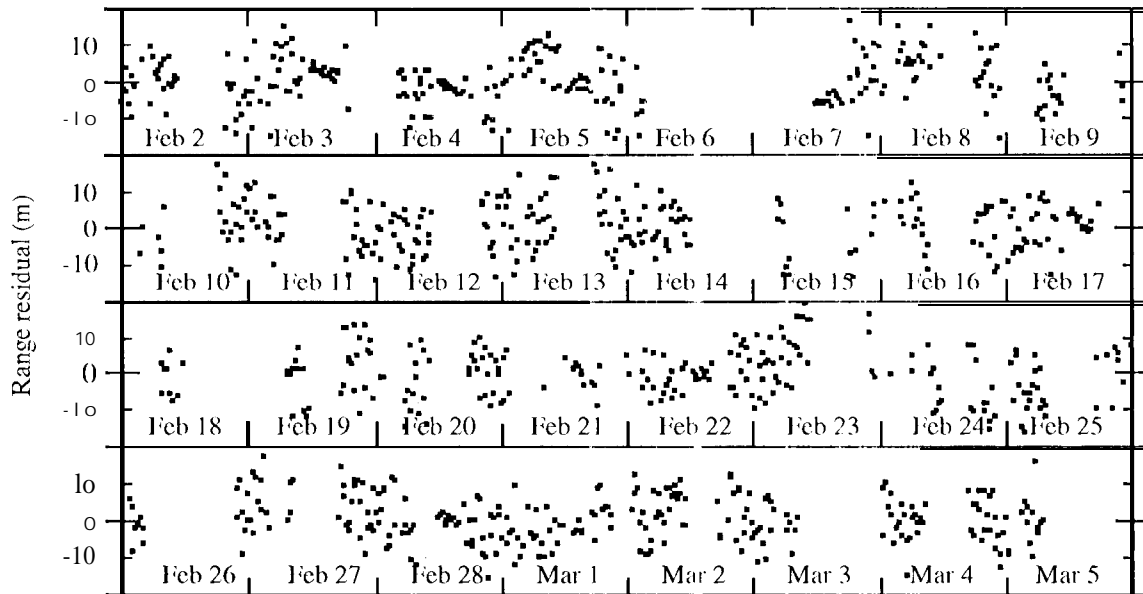Figure 1. Voyager 1 S-band Doppler data residuals

Figure 2. Voyager 1 S-band range residuals

Tables 3 and 4 give the estimated position of Jupiter at a time near the closest approach of the Voyager 1 spacecraft in Cartesian and spherical coordinates. Because Jupiter is within the solar system, the light-time significantly affects the apparent position of Jupiter. To avoid complications of light-time calculation, time transformations, and other effects, Tables 3 and 4 give the instantaneous Earth-Jupiter vector in the IERS celestial reference frame. That is, the Earth-Jupiter vector is the difference between the position of Jupiter at the specified solar-system barycentric coordinate time (TDB) and the position of the Earth at the same coordinate time. For reference the Earth-Jupiter vector is also given in the widely available ephemeris DE200.

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Table 3. Cartesian coordinates of Jupiter on 5-Mar- 1979 12:00:00.000 TDB

	x(km)	y(km)	z(km)
Estimated position	-339109994	536319388	241482423
Position in DE200	-339110282	536319389	241481691

Table 4. Spherical coordinates of Jupiter on 5-Mar-1979 12:00:00.000 TDB

	range (km)	right ascension	declination
Estimated position	678931392±38	9h 9m 13.1531 ± 0.0005s	20° 50" 6.487"±0.028"
Position in DE200	678931276	8h 9m 13.1584s	20° 50'6.262"

The uncertainties in Table 4 correspond to 40 nrad in right ascension and 140 nrad in declination. The given uncertainties are expected to reflect the actual uncertainties as realistically as possible. The actual uncertainties are dependent on the spacecraft thruster firing history which cannot be easily reconstructed at this late date. As a check for errors in modeling assumptions, separate fits were made using only the first 16 days of data within the arc and with only the last 16 days of data. In each case the estimated position of Jupiter agreed with the value given in Table 3 within 1-sigma. The uncertainty in the Earth-Jupiter range is due to not having the ranging system calibrations available for the re-analysis. The right ascension and declination estimated for Jupiter are more accurate than any other measurements except for the VLBI data taken from the Ulysses spacecraft [17]. The only other position measurement with comparable accuracy is from observations of the satellites of Jupiter with with the Very **Large** Array which determined the position of Jupiter with an accuracy of 125 nrad in right ascension and declination.[18] The Voyages 1 position determination will make a significant contribution to determining the ephemeris of Jupiter prior to Galileo's encounter in December 1995.

ACKNOWLEDGMENTS

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